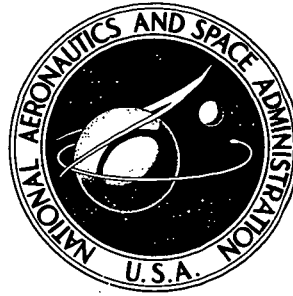


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PERFORMANCE OF 40-MILLIMETER-BORE
BALL BEARINGS WITH LEAD- AND
LEAD-ALLOY-PLATED RETAINERS IN
LIQUID HYDROGEN AT 1.2 MILLION DN

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16. Abstract <p>Forty-millimeter-bore ball bearings with lead- and lead-alloy-coated retainers were operated in liquid hydrogen at 30 000 rpm under a thrust load of 1780 N (400 lb). Four different substrate materials were used for the retainer. Longer bearing run times were achieved with a lead-tin-copper alloy coating plated onto a leaded-bronze material (22.5 hr) and an aluminum-bronze alloy (19.3 hr). One bearing with a pure-lead coating achieved the desired objective of 10 hr. This bearing had an aluminum-bronze substrate retainer and ran successfully for 12.4 hr. Additions of antimony to the lead provided an alloy coating with better wear resistance than pure lead; however, this coating was abrasive to the outer-race lands.</p>					
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PERFORMANCE OF 40-MILLIMETER-BORE BALL BEARINGS

WITH LEAD- AND LEAD-ALLOY-PLATED RETAINERS

IN LIQUID HYDROGEN AT 1.2 MILLION DN

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SUMMARY

Coatings of lead and lead alloys on various metal substrates were investigated for use as retainers for high-speed ball bearings operating in liquid hydrogen. The 40-millimeter-bore-size bearings were run at 30 000 rpm with a 1780-newton (400-lb) thrust load. The liquid-hydrogen flow through the bearing was approximately 0.0076 cubic meter per minute (2 gal/min). Coatings of lead, antimony-lead alloy, and indium-lead alloy were ion-plated onto the metal substrate. An electroplated copper-lead-tin alloy coating was also used. The four metal substrates used were an aluminum-bronze alloy, a hard aluminum-bronze alloy, a leaded bronze alloy, and an AISI 440C stainless steel.

Five bearings surpassed the objective 10-hour run time. Four of these bearings used retainers electroplated with the copper-lead-tin alloy. A run time of 22.5 hours was achieved by using a 50-micrometer-(0.002-in.-) thick coating. Seven bearings were run with a pure-lead coating ion-plated onto the retainer with the coating thickness ranging from 10.2 to 40.6 micrometers (0.0004 to 0.0016 in.). Of these seven bearings, only one with a coating thickness of 36 micrometers (0.00014 in.) exceeded the 10-hour run time. Additions of 1 and 3 percent antimony to the lead improved coating wear resistance, even though the 3-percent alloy was abrasive to the bearing outer race.

INTRODUCTION

The NERVA (Nuclear Engine for Rocket Vehicle Application) engine turbopump requires ball bearings with a radiation-resistant, nonspalling, solid lubricant. Bearings used in a cryogenic application usually depend on a self-lubricating retainer material to

perform the lubricating function. Self-lubricating retainer materials function by means of a film transfer mechanism (ref. 1). Studies have been made to find a suitable self-lubricating retainer material that can withstand an integrated gamma radiation dose of 10^5 to 10^7 joules per kilogram carbon without appreciable degradation of the mechanical properties (refs. 2 and 3). In reference 4, a lead-coated aluminum-bronze alloy showed promise as a retainer material in liquid hydrogen. Although these results (ref. 4) were not obtained under irradiated conditions, the materials used should have the necessary properties to operate in a radiation environment. It was concluded that longer bearing life could be achieved by using more wear resistant substrate materials and/or coatings. Furthermore, use of outer-race riding retainers that tend to be self-balancing as they wear should result in an improvement over the inner-race riding retainers used in reference 4.

The objectives of this investigation were (1) to achieve a 10-hour bearing operating life with a lead or lead-alloy coating on a metal retainer, (2) to determine a nominal thickness of the lead or lead-alloy coating necessary for a 10-hour run, and (3) to improve the wear resistance of the coating and the retainer substrate material while maintaining lubrication.

Experiments were conducted with 40-millimeter-bore ball bearings operating in liquid hydrogen at 30 000 rpm with a 1780-newton (400-lb) thrust load. Bearing lubrication was effected by the transfer of lead or lead-alloy film from the retainer ball pockets to the race grooves. The bearing retainers were fabricated from two aluminum-bronze alloys, a leaded-bronze alloy, and AISI 440C stainless steel. The retainers were then ion-plated or electroplated with lead or lead alloys.

APPARATUS

Bearing Test Rig

The test apparatus is shown in figure 1. The test bearing was driven through a gear assembly by a variable-speed, direct-current motor. Automatic speed control (to within ± 0.1 percent) was provided over a range of test-shaft speeds from 900 to 30 000 rpm. The test shaft was supported at its lower end by the test bearing and at its upper end by an oil-lubricated ball bearing. Thrust load was applied to the test-bearing housing by a deadweight load. A schematic view of the test-bearing mounting and support housing is shown in figure 1. The test-bearing outer-race temperature was monitored with a platinum resistance sensor (fig. 1) and continuously recorded on a strip chart. Speed was indicated on a digital frequency meter. Motor power consumption was determined from readings of a voltmeter and an ammeter (armature power).

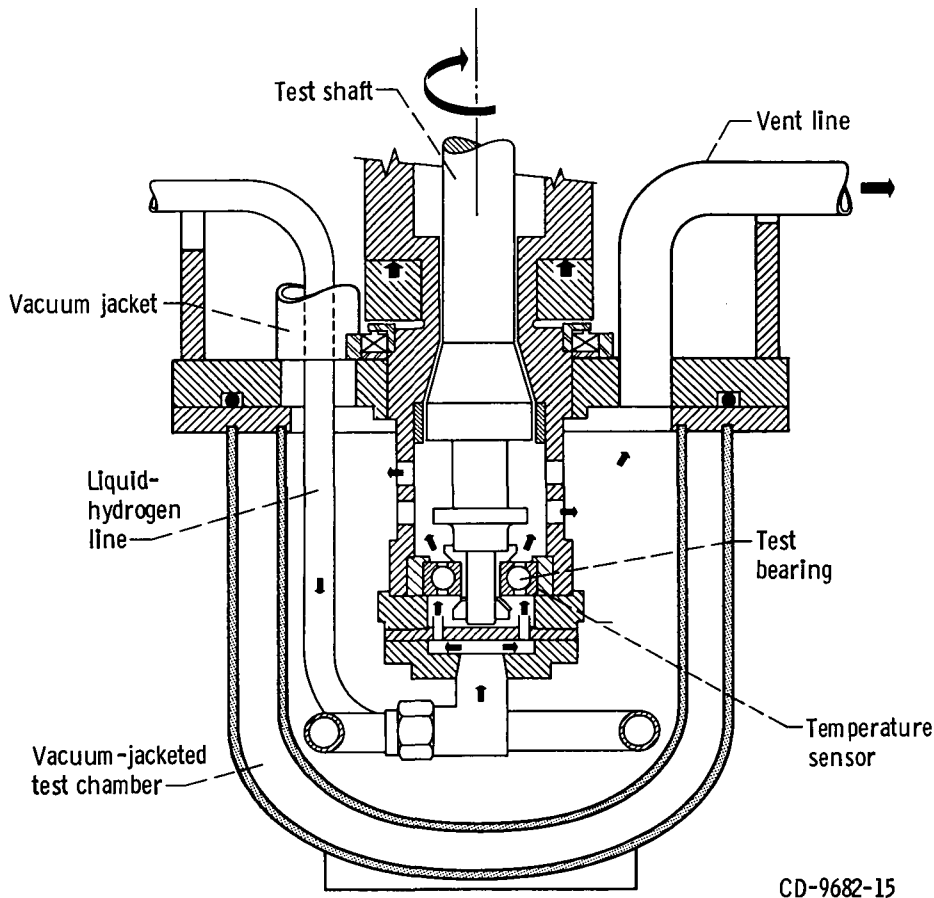


Figure 1. - Liquid-hydrogen bearing test apparatus.

Liquid-Hydrogen Supply and Exhaust System

The test bearing (fig. 1) was cooled by liquid hydrogen supplied from a 1.89-cubic-meter (500-gal) Dewar. The liquid-hydrogen flow rate to the test bearing was approximately 0.0076 cubic meter per minute (2 gal/min). The liquid-hydrogen flow from the Dewar was regulated by the Dewar pressure and the flow valve setting.

Test Bearings and Retainers

The bearings used in these tests were 40-millimeter-bore (108 series), deep-groove ball bearings manufactured to ABEC-5 tolerances. One shoulder on the inner race was relieved to make the bearings separable. The inner- and outer-race curva-

TABLE I. - RETAINER SUBSTRATE AND COATING MATERIALS

(a) Substrates

Substrate	Material	Composition		Brinell hardness number	Equivalent Rockwell A hardness
		Element	Percent		
A	Aluminum-bronze alloy	Copper Aluminum Iron Other	85.3 10.5 3.5 .7	187	55.7
B	Leaded-bronze alloy	Copper Lead Tin	75.0 20.0 5.0	57	----
C	AISI 440C stainless steel	-----	----	560	79.0
D	Hard aluminum-bronze alloy	Copper Aluminum Iron Other	82.0 13.1 4.4 .5	285	65.6

(b) Coatings

Coating	Material	Composition		Density, g/cm ³	Order of hardness (a)
		Element	Percent		
a	Ion-plated lead	Lead	99.9	^b 11.34	1
b	Electroplated lead-tin-copper alloy ^c	Lead Tin Copper	87.5 10.0 2.5	^d 10.88	3
c	Ion-plated lead-antimony alloy	Lead Antimony	97.0 3.0	^d 11.20	5
d	Ion-plated lead-antimony alloy	Lead Antimony	99.0 1.0	^b 11.29	4
e	Ion-plated lead-indium alloy	Lead Indium	70.0 30.0	^d 10.13	2

^aHigher hardnesses have higher numbers.^bFrom ref. 6.^cWith 1.25- μ m (50- μ in.) electroplated primer of 90-percent-lead-10-percent-tin alloy.^dCalculated value.

tures were both 0.54. The average internal radial clearance was 0.063 millimeter (0.0025 in.). The ball and race material was AISI 440C stainless steel.

The retainers were outer-race located and of one-piece construction machined from one of four different substrate materials. Composition and hardness of substrates are given in table I. The retainer locating surfaces were two raised rails or lands, as shown in figure 2. The rails were approximately 2 millimeters (0.080 in.) wide and 0.2 millimeter (0.008 in.) high. The diametral clearance of the retainer rail with the outer-race shoulder (i.e., the land clearance) ranged from 0.53 to 0.79 millimeter (0.021 to 0.032 in.), whereas the ball pocket clearance ranged from 0.48 to 0.76 millimeter (0.019 to 0.030 in.) as indicated in table II.

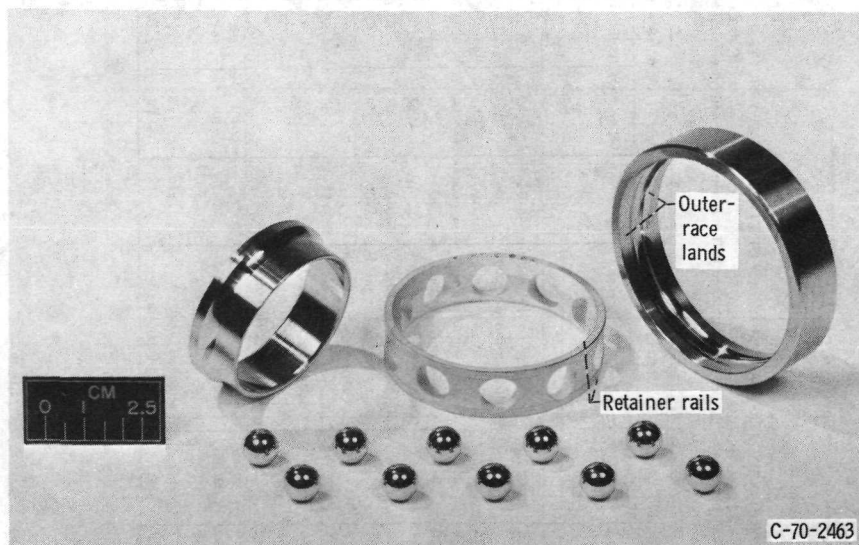


Figure 2. - Typical outer-race riding retainer and bearing (bearing 12). Retainer material, hard aluminum-bronze alloy; coating material, 70-percent-lead - 30-percent-indium alloy; thickness of coating, 34.4 micrometers.

Retainer Coatings

Lead or lead-alloy coatings, plated on the retainer substrate material, served as the bearing lubricant in the liquid-hydrogen environment. Coatings were applied by either an ion-plating or electroplating process. Coating composition, method of application, and density are given in table I. Coating thickness, which varied from 10.2 to 50.8 micrometers (0.0004 to 0.002 in.), is given in table II. Ion-plated coating thickness was assumed uniform on the retainer surface and was determined by dividing the weight gain by the product of the weight density and the surface area. The lead-tin-copper alloy was electroplated on the retainer surfaces 50.8 micrometers (0.002 in.) thick over a flash coating of 90 percent lead and 10 percent tin. The flash coating served as a primer to improve adherence to the substrate.

TABLE II. - RETAINER SPECIFICATIONS AND SUMMARY OF BEARING TEST RESULTS

[Test bearings were deep-groove ball bearings, separable at inner race; bore diameter, 40 mm; race and ball material, AISI 440C stainless steel; number of balls, 10; ball diameter, 9.53 mm (0.375 in.); inner- and outer-race curvature, 0.54; radial clearance, 0.0063 cm (0.0025 in.)]

Bearing	Retainer material		Coating thickness on retainer		Retainer clearance after plating				Run time at 30 000 rpm, hr	Mode of failure	Weight change, percent			Sliding distance at outer race		Retainer wear rate, g/Mm	
	Substrate	Coating	μm	in.	Outer race		Ball pocket				Inner race	Outer race	Ball set	Retainer	m		ft
					mm	in.	mm	in.									
1	A	a	10.2	0.0004	0.56	0.022	0.58	0.023	3.5	Excessive power input; coating worn through	0.04	0.09	-0.06	-0.45	1.2x10 ⁶	4.0x10 ⁶	0.17
2	A	a	10.2	.0004	.64	.025	.61	.024	4.7	Coating worn through	(b)	(b)	(b)	-3.59	1.5	4.9	1.16
3	B	a	33.5	.0013	.53	.021	.56	.022	2.1	Coating worn through	.02	.02	-0.01	-1.49	.7	2.3	1.16
4	B	a	27.4	.0011	.69	.028	.51	.020	3.1	Coating worn through	(b)	.01	(b)	-.85	.9	3.1	.52
5	C	a	33.8	.0014	.76	.030	.53	.021	3.6	Coating worn through	.01	-.02	-.08	-2.63	1.3	4.1	.96
6	D	a	40.6	.0016	.71	.028	.56	.022	2.7	Retainer fractured	(b)	-.03	.03	-1.11	.5	1.6	.96
7	D	a	35.8	.0014	.71	.028	.53	.021	12.4	Excessive power input; coating worn through	.06	-.12	-.31	-4.14	3.8	12.6	.48
8	C	c	49.5	.002	.66	.026	.48	.019	6.7	Retainer fractured	-.19	-.56	-2.29	-3.33	2.1	6.9	.76
9	D	c	27.4	.0011	.79	.032	.76	.030	7.6	Coating worn through	-.01	-.09	-.07	-.83	2.2	7.2	.16
14	D	d	30.0	.0012	.71	.028	.53	.021	1.2	Excessive power input; coating peeled off	.09	.01	.07	-1.68	.5	1.5	1.48
12	D	e	34.4	.0013	.56	.022	.66	.026	4.0	Coating worn through	(b)	(b)	(b)	-.74	1.2	4.0	.33
10	B	b	50.8	.002	.53	.021	.51	.020	22.5	Coating worn through	(b)	(b)	(b)	-2.65	6.5	21.3	.23
15	B	b	50.8	.002	.71	.028	.49	.020	15.2	Retainer cracked	-.03	-.01	-.03	-2.67	4.7	15.5	.57
11	D	b	50.8	.002	.76	.030	.61	.024	12.2	Retainer fractured	.07	-.43	-.06	-8.91	5.0	16.4	.79
13	D	b	50.8	.002	.69	.028	.48	.019	19.3	Coating worn through	-.01	-.25	-.20	-2.71	6.9	22.6	.17

^aRefer to material specifications in table I.

^bNegligible.

PROCEDURE

Pretest Procedure

In preparation for testing, the bearings were first degreased with three solvents (trichloroethylene, acetone, and alcohol). Next, they were inspected and measured for clearances. Finally, individual components of the bearings were weighed.

Test Procedure

After the test bearing was installed, the test chamber and all hydrogen lines were purged for 15 minutes with helium gas. Liquid hydrogen was then force-fed to the bearing and test chamber. The test shaft was rotated at 900 rpm during the 10-minute cool-down period. The thrust load was applied immediately after the start of rotation. When the system reached liquid-hydrogen temperature (20.3 K), the shaft speed was increased to the test speed of 30 000 rpm in increments of 5000 rpm every 5 minutes.

The 1.89-cubic-meter (500-gal) supply of liquid hydrogen normally provided enough fluid for a 4-hour bearing test run. The liquid-hydrogen flow rate to the test bearing during operation was approximately 7.6×10^{-3} cubic meter per minute (2.0 gal/min) over a range of supply pressures from 127.5×10^3 to 189.5×10^3 newtons per square meter absolute (18.5 to 27.5 psia).

The operating life of a test bearing in liquid hydrogen was established as the total running time that the bearing could endure at the test conditions specified previously before the coating on the retainer had worn through to the substrate material. A bearing test was suspended prematurely if (1) the bearing seized abruptly, or (2) the power input to the drive system exceeded 10 kilowatts (table II).

Post-Test Inspection of Bearings

After each run, the test bearing was inspected for wear while in position. Periodically, the bearing was removed, washed with three solvents (trichloroethylene, acetone, and alcohol), and dried and weighed to determine the weight change (in mg) of each component. The balls, races, and retainers were examined visually and with optical microscopy to determine the extent of wear and surface damage. Photographs of the retainers were made to illustrate the wear patterns that occurred during the test period.

RESULTS AND DISCUSSION

Lead Coatings

The pure-lead coatings were applied to the retainers of bearings 1 to 7 by the ion-plating technique described in reference 5. Coating thickness for these seven bearings varied from 10.2 to 40.6 micrometers (0.0004 to 0.0016 in.). All four substrate retainer materials investigated are described in table I. In contrast with reference 4, the present work showed no correlation between lead coating thickness and bearing life.

A 12.4-hour run time was obtained with bearing 7. The lead-transfer film thickness on bearing 7 was excessive and caused the lead to blister and peel off in ribbons as shown in figure 3. The retainer substrate used for bearing 7 was a hard aluminum-

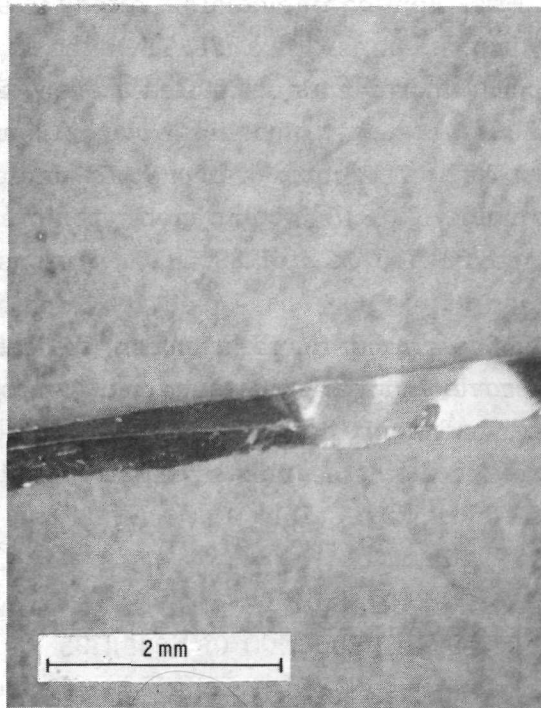


Figure 3. - Ribbon of lead transfer film removed from outer-race ball track of bearing 7 after 12.4 hours of run time.

bronze alloy (material D, table I) with a 38-micrometer- (0.0015-in.-) thick lead coating. Visually, wear of the retainer substrate material from the rail area had occurred mostly on one side of the retainer (see also fig. 4). Lead smearing back onto the rail wear areas from adjacent areas of the outer diameter of the retainer may have contributed to the longer useful life of bearing 7. The results from reference 4 and

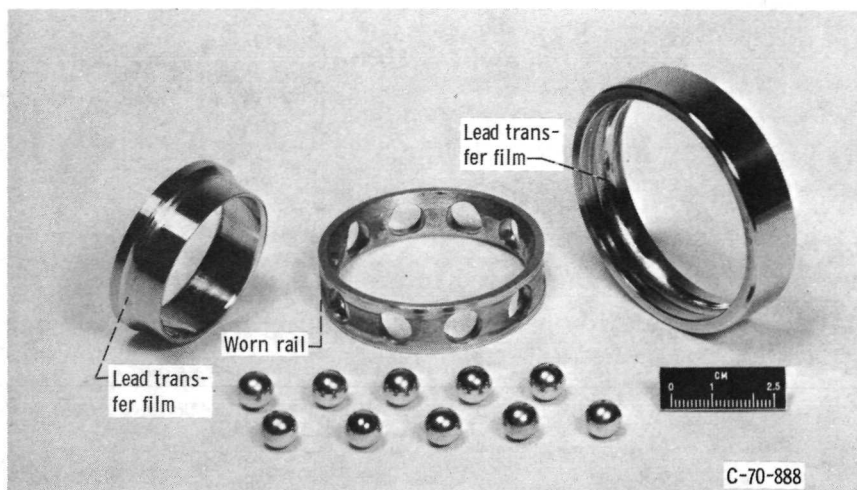


Figure 4. - Bearing 7 after 12.4 hours of run time at 30 000 rpm. Retainer material, hard aluminum-bronze alloy; coating material, pure (99.9 percent) ion-plated lead; thickness of coating, 35.8 micrometers.

from this investigation indicate that both electroplated and ion-plated lead transfer satisfactorily from the retainer surfaces to lubricate the balls and race grooves.

The retainer of bearing 6 fractured after running 2.7 hours. The failure mode for all other bearings of this group was by wear-through of the lead coating to the substrate material. Run times for bearings in this group (with the exception of bearing 7) were less than 10 hours, as shown in table II. These test results indicate that the coating was not sufficiently wear resistant to provide lubrication for the desired 10-hour run time. A harder coating should improve the wear resistance and thereby increase the operating life of the bearing. Since lead can be hardened by alloying, several lead alloys were plated onto the retainers to determine the effect on the bearing life.

Lead Alloy Coatings

Lead-antimony alloy (97-percent Pb, 3-percent Sb). - In the investigation of reference 6, lead was hardened by additions of 1 to 9 percent antimony. Therefore, to increase the wear resistance of the lead coatings applied to the bearing retainers, a lead alloy containing 3 percent antimony was ion-plated onto a 440C stainless steel retainer (bearing 8) and onto a hard aluminum-bronze retainer (bearing 9).

As shown in figure 5, the retainer of bearing 8 fractured through the ball pockets after running 6.7 hours. Postrun examination indicated that the retainer rails had worn deeply into the bearing outer-race lands, while the retainer and the coating had experienced little wear. Apparently, the hard phase (undissolved antimony) acted as an abrasive and wore the locating shoulders of the hardened 440C stainless steel outer race.



Figure 5. - Failure of bearing 8 after 6.7 hours of run time at 30 000 rpm. Retainer material, AISI 440C stainless steel; coating material, 97-percent-lead - 3-percent-antimony alloy; thickness of coating, 49.5 micrometers.

Bearing 9, using a hard aluminum-bronze retainer substrate, ran for 7.3 hours before the lead alloy coating wore through. The wear of the outer race of bearing 9 was not as severe as that found with bearing 8. A comparison of the outer-race wear between the two bearings can be made by examining table II.

Lead-antimony alloy (99-percent Pb, 1-percent Sb). - In an attempt to reduce wear of the bearing outer-race land, a softer lead-alloy coating containing 1 percent antimony was evaluated. A 30-micrometer- (0.0012-in.-) thick coating was ion-plated onto the hard aluminum-bronze retainer of bearing 14. Bearing 14 ran 1.2 hours at 30 000 rpm before an excessively high motor power indicated a bearing problem.

Inspection of the bearing revealed that part of the ion-plated 99-percent-lead - 1-percent-antimony coating had not adhered to the retainer substrate in the critical sliding areas. Fragments of the coating lodged in the ball pockets and thus jammed the bearing.

Lead-indium alloy (70-percent Pb, 30-percent In). - Reference 7 indicates that indium can be alloyed with lead to increase material hardness. Therefore, a 70-percent-lead - 30-percent-indium coating was ion-plated onto a hard aluminum-bronze retainer. The retainer was used in bearing 12 and ran successfully at 30 000 rpm for 4 hours. Postrun examination showed no abrasive wear on the bearing outer land. This observation was confirmed by the negligible outer-race weight loss shown in table II for bearing 12. Bearing operation had to be discontinued because of uneven rail wear and high wear of the coating in the ball pockets. Examination of the retainer indicated the ball pockets were thinly coated in comparison to the rest of the retainer surface. During the ion-plating process, the retainer surface was apparently at a temperature higher

than the melting point of the lead-indium alloy. Therefore, some of the coating ran as it was applied, and the result was a nonuniform coating thickness. This uneven distribution of the coating resulted in an unbalanced retainer. Postrun inspection showed that most of the retainer rail wear occurred on the rail adjacent to the heavily coated end, as shown in figure 6.

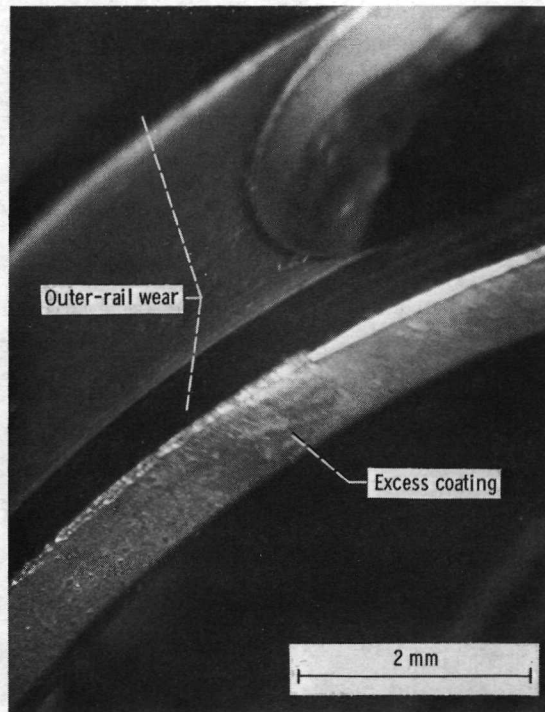


Figure 6. - Retainer showing uneven coating thickness and rail wear after 4 hours of run time (from bearing 12). Coating material, 70-percent-lead - 30-percent-indium alloy.

Lead-tin-copper alloy (87.5-percent Pb, 10-percent Sn, 2.5-percent Cu). - A lead-tin-copper alloy was electroplated onto the retainers of bearings 10, 11, 13, and 15. Two different substrate materials were used. The leaded-bronze alloy (material B, table I) was used with bearings 10 and 15, and the hard aluminum-bronze alloy (material D, table I) was used with bearings 11 and 13. The retainer was flash plated with a primer coat of 90-percent-lead and 10-percent-tin alloy. The primer was used to improve the adherence of the 50.8-micrometer- (0.002-in. -) thick coating to the substrate.

The lead-tin-copper alloy coatings provided the longest bearing run times of all coatings evaluated. All four bearings completed the objective 10-hour run time at 30 000 rpm in liquid hydrogen. The run times of bearings 10 and 13 were 22.5 and

19.3 hours, respectively. These runs were discontinued because post-test examination of retainers revealed wear-through of the lead coating on the rails and in the ball pockets. Bearings 11 and 15 also exceeded the objective of 10 hours (12.2 and 15.2 hr, respectively). These runs were terminated because of fracturing of the retainer.

The wear process appears to be as follows. As the transfer film is worn away, it is replenished from other areas of contact (rails and ball-pockets) until lead is no longer available. Rapid wear ensues once the transfer film is depleted.

The longest bearing lives were achieved with the lead-tin-copper alloy coatings. The coating was somewhat abrasive, as shown by the wear grooves formed in the outer-race lands of bearings 11 and 13. Evidence of this wear is indicated in table II by noting the outer-race weight loss of these two bearings. The 50.8-micrometer- (0.002-in.-) thick lead-alloy coating in the ball pockets of bearing 13 tended to extrude into the wear track and jam the balls. This phenomenon occurred primarily during the initial bearing run and prevented the bearing from achieving the 30 000-rpm test speed. After the extruded material was removed from the retainer, the bearing was reassembled and testing was continued. This extrusion phenomenon may indicate the need to optimize the coating thickness to achieve trouble free operation.

Effect of Retainer Substrate Material

One common problem with the metal retainers used in this investigation was that 4 out of 15 fractured. The retainer of bearing 15 had one crack in the ball-pocket region, whereas in bearings 6, 8, and 11 the retainers fractured into several pieces through the ball pockets. Retainers 6 and 11 were fabricated from hard aluminum-bronze alloy, retainer 15 was fabricated from the softer leaded-bronze material. The fact that retainer 8 was machined from hardened stainless steel and had the smallest ball pocket clearance may have caused its fracture.

Lead coatings. - The aluminum-bronze retainer material used for bearings 1 and 2 was the same retainer substrate material used for all bearings investigated in reference 4. The material lubricated well but did not have sufficient wear resistance to preclude retainer failure once the lead coating had worn through. Use of a leaded-bronze material for the retainers of bearings 3 and 4 did not achieve longer life even though the lead coating was thicker.

In reference 8, the use of lead coatings on 440C stainless steel disks in liquid-hydrogen friction and wear tests is discussed. Results indicated that galling of the surfaces does not take place immediately after the lead coating has worn through. An AISI 440C stainless steel retainer was ion-plated with 33.8-micrometer- (0.0014-in.-) thick lead and used in bearing 5. The lead coating and rails on the outer surface of the

retainer, which were approximately 0.2 millimeter (0.008 in.) high, completely wore off 120° around the outer periphery. Although the amount of wear was considerable for a hardened stainless steel substrate material, there was very little indication of galling, which indicated the lubricating ability of the lead. The thick transfer film on the outer-race lands appeared to be a combination of lead embedded with stainless steel wear debris. The lead transfer film was ribbon-like in certain areas.

Thicker lead coatings were plated on the harder aluminum-bronze retainers of bearings 6 and 7 than were used on the softer aluminum-bronze retainers of bearings 1 and 2. Bearing 6 failed catastrophically after running 2.7 hours at 30 000 rpm. There was evidence of abnormal wear on the upper areas of the ball pockets. Bearing 7, however, completed 12.4 hours of run time. Running was discontinued when the retainer rails began to show excessive wear (see fig. 4). The other bearing components were still in good condition.

Lead-alloy coatings. - Wear resistance or hardness of the substrate material did not appear to be a factor in the lives of bearings 9, 14, and 12. These bearings used either a lead-antimony or lead-indium alloy coating plated on the same hard aluminum-bronze substrate. Bearing 8 used a 440C stainless steel substrate retainer plated with a 99-percent-lead - 1-percent-antimony alloy. The wear of the stainless steel retainer was not discernible, probably because of the highly wear-resistant lead-antimony coating used. This retainer fractured, however, after running 6.7 hours. Subsequent bearings that used the lead-tin-copper alloy coating used either substrate B or D (table I). Bearings 10 and 15 used the soft leaded-bronze material (substrate B), whereas bearings 11 and 13 used the hard aluminum-bronze material (substrate D). The hardness of the retainer substrate material for these four bearings seemed to have no effect on the wear life of the lead-tin-copper alloy coating.

Retainer Wear Rate

The wear of the coating and substrate materials of the individual bearing retainers was discussed somewhat in the previous section. Table II shows the retainer wear for each bearing as the weight change in percent of the original retainer weight. Also shown in table II is the retainer wear rate in grams per million meters of sliding distance of the retainer outer diameter on the bearing outer race. The sliding distance is the total distance traveled by the retainer at all speeds including that of 30 000 rpm.

Generally, wear on the retainer rails was uneven around the periphery. Wear and deformation in the ball pockets was quite high as illustrated in figure 4 for bearing 7. The retainers of bearings 2, 5, 7, 8, 10, 11, 13, and 15 all had high, uneven wear. These retainers had more than 2-percent weight loss for their total running times.

Bearings 1, 9, and 12 had retainer wear less than 2 percent. Outer diameters and ball pockets of these retainers showed uniform, moderate coating wear and minimal substrate wear.

The wear rate of the various retainer coating and substrate materials can be compared by observing the bar graph in figure 7. Bearings that failed as a result of a

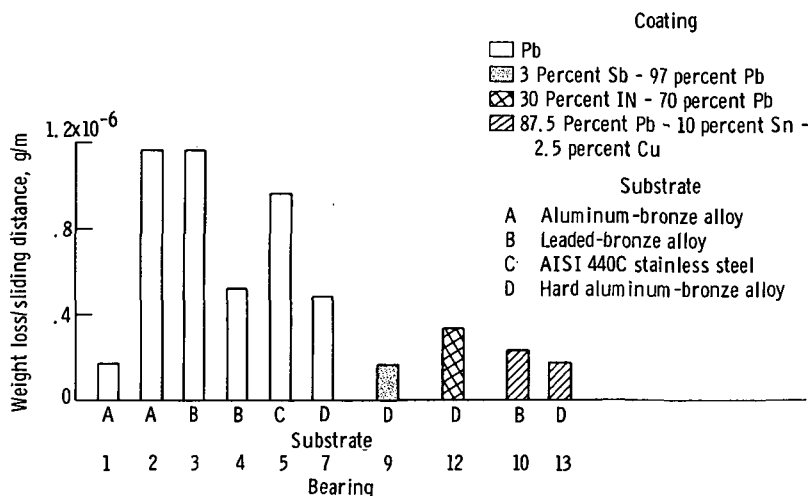


Figure 7. - Retainer weight loss per unit sliding distance for various coated retainer-substrate materials.

broken retainer or peeled coating were excluded from the plot. The lead-alloy coated retainers had lower wear rates than those with the pure-lead coating. Of the bearings shown in figure 7, only 1, 9, and 12 accurately represent coating wear since these retainers had minimal substrate wear. Retainer 7, with lead coating, and retainers 10 and 13, with lead-tin-copper-alloy coating, achieved the required 10-hour life with relatively low wear rates. The leaded-bronze alloy (material B) or the aluminum-bronze alloy (material D) served equally well as retainer substrate materials.

CONCLUDING REMARKS

Of the 15 bearings discussed in this report, 8 failed from high, uneven wear on the outer rails of the retainer. The ball pockets of the failed retainers showed moderate wear and deformation. Four retainers failed by cracking or fracturing. These problems with the substrate indicate that the retainer material may not have been ductile enough even though it had good wear resistance and was nongalling. Since some of the lead- and lead-alloy-coated retainers operated for more than 10 hours, it is apparent

that lead does lubricate at liquid-hydrogen temperatures. Early failure of some retainers indicated that other factors, such as retainer balance and bearing stability at the high rotational speed, affect the life of the bearing.

SUMMARY OF RESULTS

Coatings of lead and lead alloys on metal retainer substrates were investigated for use with high-speed ball bearings operating in liquid hydrogen. The bearings were 40-millimeter-bore size and were run at 30 000 rpm with a 1780-newton (400-lb) thrust load. The liquid-hydrogen flow through the bearing was approximately 0.0076 cubic meter per minute (2 gal/min). Coatings of lead, lead-antimony alloy, and lead-indium alloy were ion-plated onto the retainer substrate. An electroplated lead-tin-copper-alloy coating was also used. These coatings were applied to retainer substrates made of two different aluminum-bronze alloys, a leaded bronze alloy, and AISI 440C stainless steel. The study produced the following results:

1. The lead-tin-copper alloy coating proved an effective lubricant with better wear resistance than the pure-lead coating. Four bearings with a 50-micrometer- (0.002-in.-) thick coating successfully completed the objective 10-hour run time.
2. Two of the substrate materials worked equally well with the lead-tin-copper-alloy coating. Bearings using the leaded-bronze substrate ran up to 22.5 hours, whereas those with an aluminum-bronze material ran up to 19.3 hours. Both of these retainer materials had a low wear rate.
3. Additions of 1 and 3 percent antimony to lead improved the coating wear resistance; however, the 3-percent alloy was abrasive to the bearing outer race.
4. A 36-micrometer (0.00014-in.) thickness of ion-plated lead on the aluminum-bronze substrate retainer material provided 12.4-hours running time. This was the only bearing with a pure-lead coating that achieved the objective 10-hour life.
5. All three bronze-alloy retainer materials had good wear resistance and were nongalling.

Lewis Research Center,
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